MACRONUTRIENTS ABSORPTION
AND DRY MATTER ACCUMULATION IN GRAIN SORGHUM

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ABSTRACT - The present study aimed to determine the curves of macronutrients and dry matter accumulation in grain sorghum DKB 599, grown in a semiarid region. A field experiment was conducted on a sandy loam eutrophic red Latosol (Oxisol) in Janaúba, State of Minas Gerais (MG), Brazil, in a randomized block design with four replications. As statistical method, a nonlinear regression, sigmoidal function with three parameters was used. After drying, the plants were weighed and ground to determine N, P, K, Ca, Mg and S concentration. Grain sorghum plants accumulate nutrients in their shoots in the following order: N> K> Ca> P> Mg> S. The highest concentrations of K and N were observed in stems and grains, respectively. In the conditions of this experiment, the most favorable time to perform nitrogen and potassium topdressing fertilization is when the plants present seven fully expanded leaves or 24 days after the emergency (DAE).

Keywords: fertilization, growth, nutrition, *Sorghum bicolor.*

ABSORÇÃO DE MACRONUTRIENTES
E ACÚMULO DE MATÉRIA SECA NO SORGO GRANÍFERO

RESUMO - Este trabalho teve como objetivo determinar as curvas de acúmulo de matéria seca e macronutrientes no sorgo DKB 599 cultivado em região semiárida. O experimento foi conduzido em campo sobre um Latossolo Vermelho eutrófico, de textura franco-argilosa, no município de Janaúba-MG, Brasil, em delineamento experimental de blocos casualizados, com quatro repetições. Utilizou-se o modelo de regressão não linear, função sigmoidal com três parâmetros como método estatístico. Após secagem, cada parte da planta foi pesada e moída para, em seguida, determinarem-se os teores de N, P, K, Ca, Mg e S. As plantas de sorgo granífero acumulam nutrientes em sua parte aérea na seguinte ordem: N > K > Ca > P > Mg > S. As maiores concentrações de K e N foram observadas, respectivamente, nos caules e nos grãos. Nas condições de condução do experimento, a época mais propícia para realizar a adubação nitrogenada e potássica em cobertura é quando as plantas apresentam sete folhas totalmente expandidas ou 24 dias após a emergência (DAE).

Palavras-chave: fertilização, crescimento, nutrição, *Sorghum bicolor.*

Sorghum (*Sorghum bicolor* L. Moench) is the staple food of more than 500 million people in more than 30 countries. It is also an excellent source of energy and extremely useful in hot and dry regions, where the cultivation of other species, such as maize, cannot achieve good yields (Ribas, 2010).

Brazil is one of the top 10 global producers, however, sorghum productivity is still low, averaging 2,476 kg ha^{-1} (Conab, 2011), compared to the productivity obtained in countries like the United States and Argentina (Duarte, 2010). Among other factors, the main reasons for this scenario are the low consumption and the inadequate application of fertilizers. In addition, little is known about the patterns of nutrient absorption and accumulation in sorghum (Damian et al., 2017).

The rusticity characteristic of sorghum does not mean that nutrients and fertilization are unnecessary. Like other annual crops, sorghum may have great nutritional requirements, especially when seeking high yields. Cantarella et al. (1997), studying the macronutrients extraction by sorghum, concluded that 17 kg of N, 4 kg of P, 5 kg of K and 1.2 kg of S are exported per ton of grains. For the whole plant, nutrient export corresponds to 30 kg of N, 6 kg of P, 23 kg of K, and 2.7 kg of S per ton of grains.

The recommendation of fertilizers is based on studies about fertilization responses and nutritional requirements of the crop. Due to the maximum absorption point in the plants, the crop requirement for nutrients cannot be inferred only from the total extraction. It is necessary to study the nutrient uptake in function of time, to predict how, when and what amount of fertilizer should be applied (Martins et al., 2017).

The scarcity of information on the nutritional requirements of high yield cultivars justify studies on their nutritional needs (how and when to apply a particular nutrient) in order to increase the efficiency in fertilization management, which will allow an increase in production and a reduction of costs in the field, due to a rational and efficient use of fertilizers and soil.

Furthermore, the available information on sorghum production in favorable environmental conditions is outdated and does not reflect the gains that may result from the combination of a modern cultivar with optimized management and edaphoclimatic factors. Therefore, the objective of this study was to determine the macronutrients absorption rate and dry matter accumulation in grain sorghum DKB 599, cultivated in the North of Minas Gerais, Brazil.

Material and Methods

The experiment was conducted with supplemental irrigation in the second half of November, in Janaúba-MG, Brazil, located at latitude 15º 47 '50 "S, longitude 43 18' 31" W and altitude of 516 m. The soil of the experimental area was classified as sandy loam eutrophic red Latosol (Oxisol) (Santos, 2013), with the following characteristics in the 0-20 cm layer: 38 dag kg^{-1} clay; pH 5.9 in water; 6.5 mg dm^3 P (Mehlich-1); 141 mg dm^{-3} K$^+$; 3.3 cmol$_c$ dm^3 Ca^{2+}; 0.7 cmol$_c$ dm^{-3} Mg^{2+}; 1.3 cmol$_c$ dm^{-3} H + Al; 3.6 dag kg^{-1} of organic matter. Chemical characterization was performed according to the procedures proposed in Donagema et al. (2011).

The grain sorghum DKB 599 was planted in density of 180,000 plants ha^{-1}. Fertilization at planting was 500 kg ha^{-1} of 04-30-10 formula, plus 1.5 kg ha^{-1} of Zn. The topdressing was divided into three applications: the first one, in the stage 4-5 fully expanded leaves with the application of 300 kg ha^{-1} of 30-00-20; the second one, in the stage 6-7 fully expanded leaves, applying 200 kg ha^{-1} of 30-00-

20; and the third application was in the stage 8 fully expanded leaves, applying 300 kg ha^{-1} of ammonium sulfate. Irrigation was performed throughout the growing season with adequate management strategy to promote good plant growth.

The experimental design was a randomized block with four replications. The plots consisted of four rows of 5 m long, spaced 0.6 m apart. Nine harvests were performed (T1 = three fully expanded leaves, T2 = five fully expanded leaves, T3 = seven fully expanded leaves, T4 = panicle differentiation; T5 = 80% total leaf area/panicle pre-emergence; T6 = all fully expanded leaves, T7 = pollen release in panicles; T8 = milky/pasty grain; T9 = black layer in the grain). The choice of harvest moment was based on the three growth stages of sorghum plant (EC1, EC2 and EC3) (Giorda, 2008; Rodrigues, 2010), adopting three samplings of plants in each stage.

All plants of the plots were cut close to the soil surface, and the samples were separated in leaves, stems, panicles and grains. The parts of the plants were washed with deionized water and dried in a forced-air circulation oven, at 65 °C; then the samples were ground in a Wiley mill.

In order to determine P, K, Ca, Mg and S concentration in the dry matter of the plant, the method described by Malavolta et al. (1997) was used, being the samples submitted to nitroperchloric digestion.   P was determined by colorimetry; K, by flame photometry; Ca and Mg, by atomic absorption spectrophotometry; and S, by turbidimetry. To determine N concentration, the samples were submitted to sulfur digestion, and the nutrient was quantified according to the Kjeldahl semi-micro method. The accumulation of nutrients in the plant in kilos per hectare was estimated by multiplying the concentrations of the elements in the plant (g kg^{-1} dry matter) by the dry matter in the shoots per hectare (kg ha^{-1}), dividing the product by one thousand.

In order to explain physiologically the total accumulation of DM and nutrients, it was used non-linear regression, sigmoidal function with three parameters described from the following equation:

$$\hat{y} = \frac{a}{1 + \exp\left[-\left(\frac{x - x_o}{b}\right)\right]}$$

In which: $\hat{y}$ = accumulation of nutrients or DM; a = upper corner points; b = adjustment parameter, and x_0 = the time when the maximum accumulation rates of DM and nutrients occurred in the plants. The maximum daily accumulation rate (MDAR, kg day^{-1}) was determined by the accumulation of DM and nutrients in x_0 minus the accumulation of the previous day.

The lower corner points (P_{cl}) and upper corner points (P_{cu}) were calculated according to Venegas et al. (1998) using the parameters of non-linear equations:

$$P_{cl} = x_0 - 2b \qquad P_{cu} = x_0 + 2b$$

In which: P_{cl} indicates the point in the accumulation curve where significant gains in DM and nutrients begin. P_{cu} indicates the moment when the accumulation of elements begins to stabilize.

The relative accumulation (RA) was obtained by the difference between the minimum and maximum accumulation in each phenological stage. The percentage values were obtained in relation to the final accumulation.

$$RA = A_F - A_I \qquad \% = (RA/AT)*100$$

In which: RA = relative accumulation at stage; AT = accumulation achieved; A_F e A_I = accumulation at the end and the beginning of the stage.

Finally, the adjustment for the grains was performed by using linear regression. The models

were chosen according to the adjustment (percentage of explained variance, R^2) and the best representation of the phenomenon.

Results and Discussion

The DM accumulation was modest from the beginning of development until the stage of seven fully expanded leaves at 24 days after emergence (DAE) equivalent to $P_{cl.}$ Later, there was an increase in DM production, which extended up to 70 DAE (end of flowering), equivalent to P_{cu}, and coming to the end of the cycle with a very low growth rate when compared to the previous period (Figure 1).

The physiological interpretation of these different growth stages is based on some basic principles. Initially, the plant depends on seed reserves for the production of organs that make up the seedling. After the root system development and the emergence of leaves, anabolic processes, dependent on photosynthesis, induce a rapid growth, reaching a definitive size. Subsequently, the plant starts a senescence stage, which results in the interruption of organic matter production (Magalhães & Durães, 2003).

The maximum DM yield was obtained only at the end of the cycle, 13,260 Kg ha^{-1} at 98 DAE, in which grains corresponded to 6,400 Kg ha^{-1}; therefore, harvest index (fraction of the grain produced in relation to DM) was equal to 0.48 (Figure 1). About 52% of the plant material remained in the soil as crop residue, accounting for approximately 6,900 Kg ha^{-1} of DM. These results are slightly lower than those obtained by Bressan et al. (2001), 14,300 Kg ha^{-1} of DM, in which 7,800 Kg ha^{-1} corresponded to grains.

The maximum daily accumulation rate (MDAR) of DM occurred at 47 DAE, stage of all fully
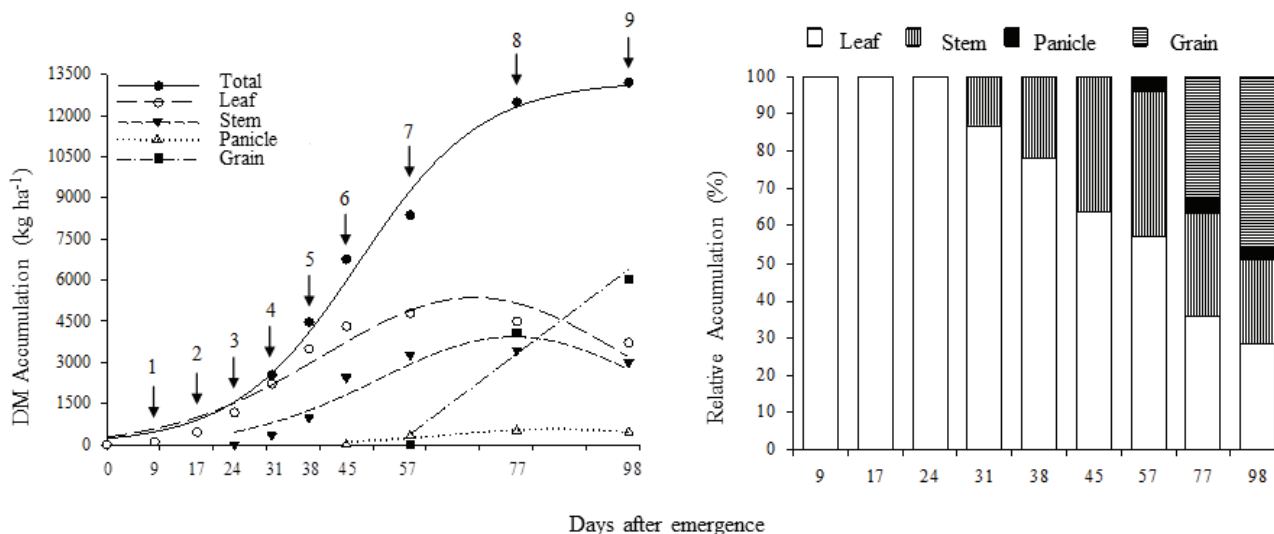
Figure 1 - DM accumulation in grain sorghum DKB 599, in kg ha^{-1}, and relative accumulation (%) in leaf, stem, panicle and grain, depending on the days after emergence. (1) three fully expanded leaves; (2) five fully expanded leaves; (3) seven fully expanded leaves; (4) panicle differentiation; (5) 80% total leaf area; (6) all fully expanded leaves; (7) release of pollen in panicles; (8) milky/pasty grain; (9) black layer in the grain.

expanded leaves, corresponding to 286.64 kg ha^{-1} (Table 1). However, the highest relative accumulation of DM per stage was only observed at flowering, corresponding to 25.1%. Additionally, from the beginning of development until flowering, more than 70% of DM accumulation was reached (Table 2).

In the black layer stage, DM production had the following sequence: grain > leaf > stem > panicle (Figure 1). It is noteworthy that the grain filling was mainly due to the accumulated reserves in different parts of the plant, especially the leaves, the stems

and, to a smaller proportion, the panicles as the main sources of photoassimilates.

After flowering, nutrient uptake is reduced as the plant approaches physiological maturity, since produced photosynthates are primarily sent to grain filling (Masclaux et al., 2008) instead of roots, which consequently lose efficiency, not supplying the grain-filling requirements. Therefore, the reserves are mobilized from leaves and stems, accelerating the senescence process and reducing the photosynthetic activity (Bresson et al., 2018).

Table 1 - Point of maximum daily accumulation rate (X_{MDAR}, DAE), maximum daily accumulation rate (MDAR, kg day^{-1}) of macronutrients, lower corner points (P_{cl}, days) and upper corner points. (P_{cu}, days).

Variable	X_{MDAR}	MDAR	P_{cl}	P_{cu}
DM	47	286.64	24	70
N	43	5.43	19	67
P	53	0.87	24	81
K	38	7.79	21	54
Ca	38	1.94	21	55
Mg	49	0.57	23	75
S	44	0.37	20	68

Table 2 - Relative accumulation (RA, kg ha^{-1}) at development stages of grain sorghum DKB 599.

Variable	1		2		3		4		5		6		7		8		9	
	RA	%	RA	%	RA	%	RA	%	RA	%	RA	%	RA	%	RA	%	RA	%
DM	465.5	3.6	433.3	3.3	660.6	5.0	1043.8	8.0	1497.7	11.4	1876.3	14.3	3288.9	25.1	3056.9	23.3	779.2	5.9
N	14.4	5.6	12.2	4.7	17.5	6.8	25.6	9.9	33.4	12.9	37.6	14.6	57.9	22.4	47.9	18.6	12.0	4.7
P	2.3	4.8	1.6	3.3	2.1	4.5	3.1	6.4	4.2	8.7	5.2	10.9	10.2	21.4	13.5	28.1	5.7	12.0
K	7.7	3.0	11.6	4.5	21.7	8.5	38.0	14.8	51.9	20.2	51.1	19.9	52.4	20.4	20.3	7.9	2.0	0.8
Ca	2.2	3.3	3.2	4.8	5.7	8.7	9.7	14.8	13.0	19.8	12.7	19.4	13.3	20.2	5.4	8.2	0.6	0.9
Mg	1.3	4.5	1.0	3.5	1.4	5.0	2.2	7.5	3.0	10.3	3.7	12.7	6.7	23.1	7.2	25.1	2.4	8.2
S	0.9	5.3	0.8	4.6	1.2	6.6	1.7	9.7	2.2	12.8	2.6	14.5	4.0	22.7	3.3	19.0	0.8	4.8

1. Three fully expanded leaves; 2. Five fully expanded leaves; 3. Seven fully expanded leaves; 4. Panicle differentiation; 5. 80% total leaf area; 6. All fully expanded leaves; 7. Release of pollen in panicles; 8. Milky/pasty grain; 9. Black layer in the grain.

The average levels of nutrients in the leaves, stems, panicle and grains in each harvest time can be seen in Table 3. K had higher concentrations in leaves and stems, being the leaves the main source of nutrients redistribution in sorghum (N and P, especially) during the stages related to grain filling.

According to Ta and Weiland (1992), during the grain-filling period there are two sources of nutrients: absorption from soil and remobilization from vegetative tissues. In a study using ^{15}N to measure the remobilization rate of N under field conditions in maize, the authors observed that the leaves and stems provided 45% of N remobilized during grain filling, while the roots contributed about 10%. Therefore, when the nutrients absorbed by the roots are not sufficient to supply the grain filling needs, nutrients are then translocated from other parts to the growing organs (Souza & Fernandes, 2006), justifying the reduction of nutrient levels as the plant develops.

Considering the Ca, it was found that the concentrations of this nutrient in the leaves showed a slight increase tendency during the sorghum cultivation cycle, opposing the observations for the grains. It confirms the hypothesis that Ca is a nutrient of difficult redistribution, accumulating in the leaves that correspond to the end of xylem (Larcher, 2006). The reduction in Ca concentration as well as the S, found in grains can be attributed to the dilution effect.

For the macronutrient absorption and accumulation rate, as well as the percentage of distribution of them in the plant (Figures 2 and 3), and the parameters of the adjusted model, the amount of accumulated macronutrients (kg ha^{-1}) in plants was directly related to the production of DM, agreeing with Fontes et al. (2017).

The total macronutrients accumulation in the shoot showed the following descending order: N (261.15 kg ha^{-1}), K (256.86 kg ha^{-1}), Ca (65.88 kg ha^{-1}), P (49.98 kg ha^{-1}), Mg (29.41 kg ha^{-1}), S (17.75 kg ha^{-1}). Therefore, special attention should be given to maintaining adequate availability of N, K and Ca, due to high demand of the crop for these nutrients.

Similar sequence was reported by Bressan et al. (2001), studying the sorghum BRS 304 in a protected cultivation environment. They observed the following accumulations: N (423.57 kg ha^{-1}), K (240.41 kg ha^{-1}), Ca (98.74 kg ha^{-1}), Mg (37.21 kg ha^{-1}), and P (28.76 kg ha^{-1}). However, Fonseca et al. (2008) observed the following order of nutrient extraction in the shoot: K> N> Ca> Mg> P> S. These results indicate that K is the first and N is the second most required nutrient by sorghum, which disagrees with the present study and with Cantarella et al. (1997), who indicate the opposite, in which sorghum has higher extraction of N compared to K. Perhaps these discordant results are due to the edaphoclimatic conditions of the sandy loam eutrophic red Latosol, which received nitrogen applications in doses that generated high consumption and the different genotypes used in the two studies.

Considering the yield and concentrations of nutrients in grains, in the T9 stage (black layer), it was possible to estimate the nutrient export by the grains, which showed the following order: 156.84 kg ha^{-1} of N; 73.62 kg ha^{-1} of K; 36.49 kg ha^{-1} of P; 19.20 kg ha^{-1} of Ca; 17.28 kg ha^{-1} of Mg and 8.32 kg ha^{-1} of S (Figures 2 and 3). These results indicate that, despite the high demand for K, more than 70% of the absorbed amount can return to the soil with the mineralization of crop residues, different from that observed for P, which 27% can return to the soil.

When the plants had seven fully expanded leaves (24 DAE), 100% of the accumulated macronutrients was allocated in the leaves, while at physiological maturity (98 DAE) this amount was

Table 3 - N, P, K, Ca, Mg and S concentrations (g kg^{-1}) in grain sorghum DKB 599, depending on the phenological stages of the crop.

| Harvest /Stage	N	P	K	Ca	Mg	S
	g kg^{-1} in leaves					
1-3 fully expanded leaves	46.3	7.7	35.3	7.2	2.3	3.2
2-5 fully expanded leaves	53.0	8.0	38.5	9.2	2.5	3.5
3-7 fully expanded leaves	31.3	5.3	35.8	9.4	2.3	2.4
4 - Panicle differentiation	30.5	3.5	30.1	8.0	2.1	1.8
5 - 80% total leaf area	23.3	3.3	22.5	7.1	2.2	1.6
6 - All fully expanded leaves	23.0	3.4	21.4	7.2	2.2	1.6
7 - Flowering	23.0	3.2	22.6	7.7	2.3	1.4
8 - Grain milky/pasty	23.5	2.7	22.5	7.8	2.2	1.3
9 - Black layer in the grain	19.8	2.2	21.9	8.1	2.3	1.3
	g kg^{-1} in stems					
4 - Panicle differentiation	24.5	3.8	50.7	10.8	2.9	1.5
5- 80% total leaf area	23.0	2.6	46.4	8.9	2.6	1.3
6 - All fully expanded leaves	22.3	2.5	38.7	7.1	2.1	1.4
7 - Flowering	18.9	2.9	36.0	5.4	1.6	1.5
8 - Grain milky/pasty	14.8	2.6	32.5	4.9	1.5	1.4
9 - Black layer in the grain	10.9	1.4	33.5	5.1	1.3	1.3
	g kg^{-1} in panicles					
7 - Flowering	28.3	3.8	17.0	4.4	1.9	1.7
8 - Grain milky/pasty	21.5	3.2	17.1	4.7	1.8	1.4
9 - Black layer in the grain	18.0	2.1	12.7	4.7	1.7	1.3
	g kg^{-1} in grains					
8 - Grain milky/pasty	20.1	5.1	8.5	3.3	2.5	1.4
9 - Black layer in the grain	24.5	5.7	11.5	3.0	2.7	1.3

Average of four repetitions.

less than 30% except for Ca. From the stage of all fully expanded leaves (45 DAE), it was possible to observe the beginning of the redistribution of these nutrients to the reproductive structures in formation (panicle) (Figures 2 and 3). However, based on these results, it is important to state that the leaves were the main source of redistribution, where the nutrients were directed mainly to the grains, as reported by Zobiole et al. (2010).

The beginning of significant gains in the accumulation of macronutrients, P_{cl}, took place from 19 to 24 DAE (5-7 expanded leaves). However, it is possible to state that the topdress application should start close to these times. Simultaneously, the beginning of stabilization, P_{cu} in macronutrient accumulation, occurred at 67 DAE for N (flowering) and 54 DAE for K (pre-flowering) (Table 1). This means that in the edaphoclimatic conditions of Northern Minas Gerais, providing macronutrients in those dates causes little influences to the final sorghum yield.

Also in the same Table, it was found that the highest maximum daily accumulation rate (MDAR) occurred between 38 and 44 DAE. This was the time of the greatest demand for macronutrients in sorghum, when it is indispensable the availability of nutrients in the soil for root absorption. For P and Mg
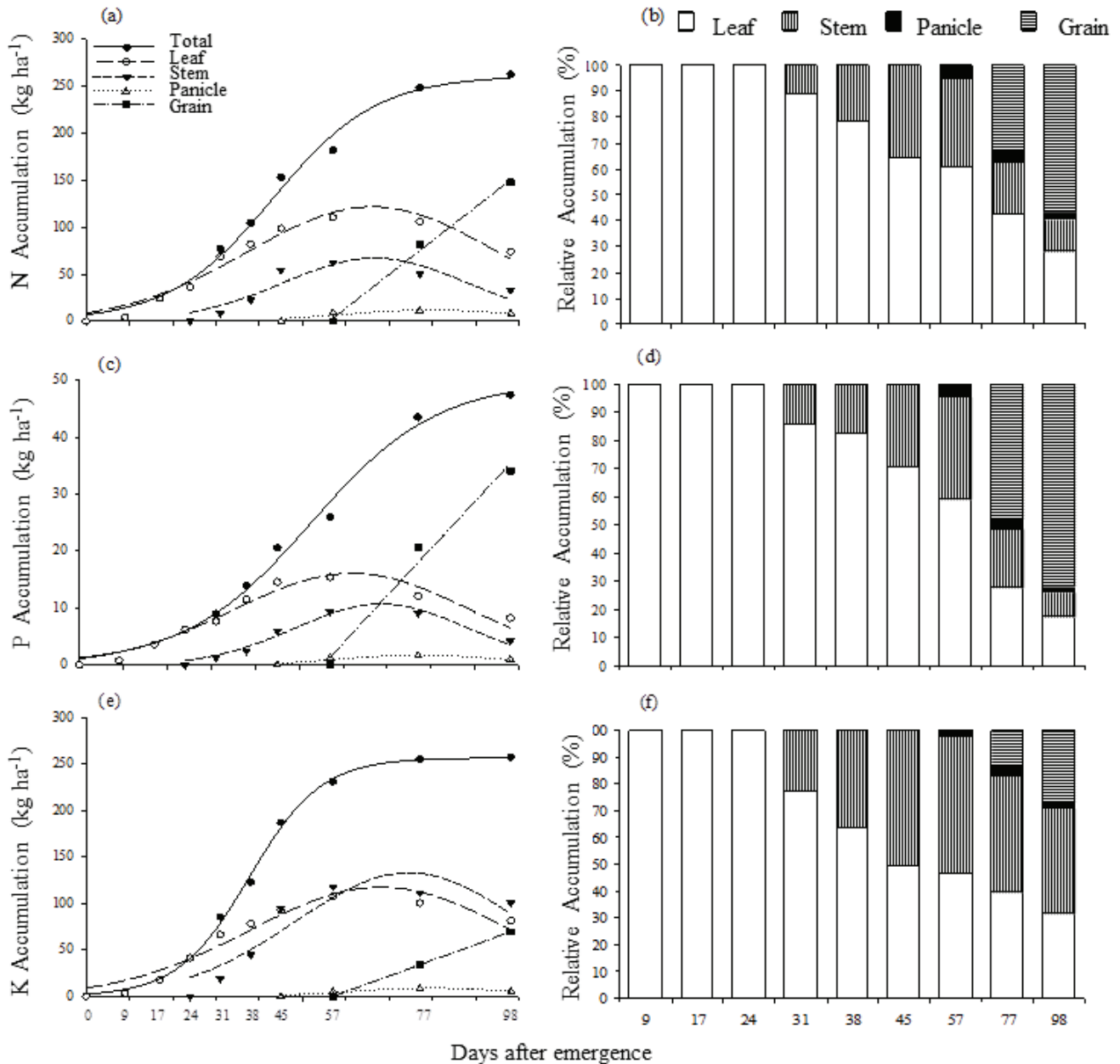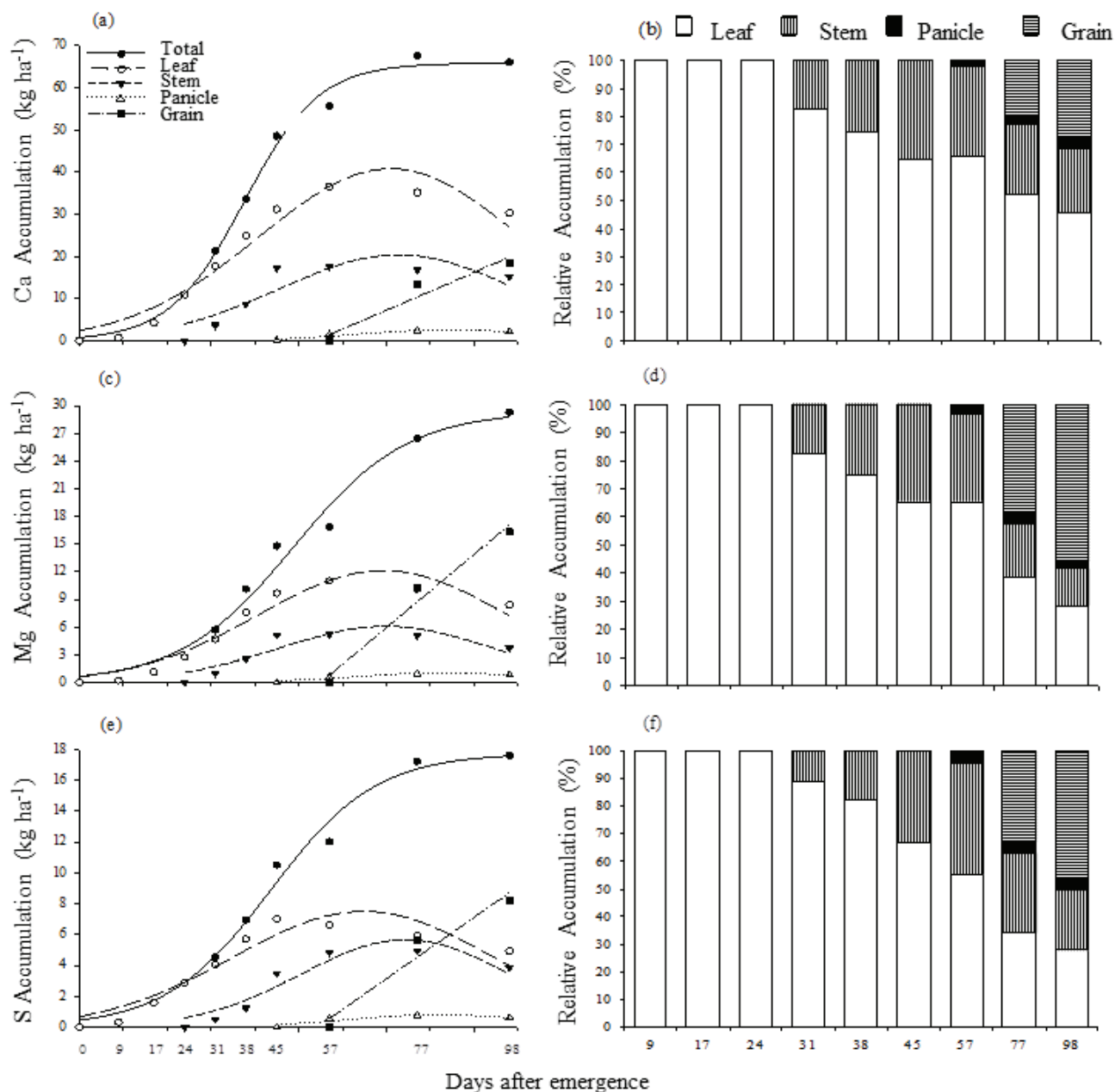
Figure 2 - N ("a" and "b"), P ("c" and "d") and K ("e" and "f") absorption and relative accumulation in leaves, stem, panicle and grains.

the most demanding periods (X_{MDAR}) occurred later, at 53 and 49 DAE respectively.

It is possible that the high rates of water translocation in stages corresponding to these times (80% of leaf area and fully expanded leaves), required

for cell expansion (Taiz & Zeiger, 2010), may cause the transport of nutrients to other tissues of the plants. Thus, it is believed that the high rates of macronutrient accumulation at this time are in part effect of water translocation. Therefore, the water deficit in these

Figure 3 - Ca ("a" and "b"), Mg ("c" and "d") and S ("e" and "f") absorption and relative accumulation in leaves, stem, panicle and grains.

stages will not only hinder the development of the plants, but also the accumulation of macronutrients necessary for metabolic processes.

In this context, considering the dynamics of N and K in the soil and their P_{cl} (19 and 21 DAE),

it would be interesting to perform the topdressing with these nutrients when plants have seven fully expanded leaves, which occurred at 24 DAE for the conditions of the experiment. Thus, there will be adequate availability of nutrients during the critical

phase of accumulation, mainly in soils with higher probability of leaching. Nonetheless, until the stage of seven fully expanded leaves, the plants accumulated 44.1 kg ha^{-1} of N and 41.0 kg ha^{-1} of K (Table 2), which corresponds to the amounts available in the soil until the topdressing application, in order to obtain high yields of grains.

The curves of N and S accumulation, as well as K and Ca showed similar behavior, because in both cases the X_{MDAR}, P_{cl} and P_{cu} showed similarity. This indicates that the accumulation of these nutrients follows the same tendency, varying only the magnitude of the accumulated amount.

Finally, the highest relative accumulations were found in flowering, except for P and Mg. It was also shown that until this stage, the plants accumulated respectively 91.3, 91, 76.9, 76.2, 66.6 and 60.0% of the K, Ca, N, S, Mg and P total amount throughout the cycle (Table 2).

It is probable that the nutrients accumulated in a greater proportion in flowering are stored mainly in the vacuole of the cells (Epstein & Bloom, 2006). Subsequently, they must be used gradually in the metabolism, according to their specific requirements along the complementary stages of grain formation.

Conclusions

Grain sorghum DKB 599 has the following order of macronutrient extraction in kg ha^{-1}: N (261.15)> K (256.86)> Ca (65.88)> P (49.98)> Mg (29.41)> S (17.75).

For each ton of sorghum DKB 599 grains, 24.5 kg of N, 11.5 kg of K, 5.7 kg of P, 3.0 kg of Ca, 2.7 kg of Mg and 1.3 kg of S are exported.

More than 70% of K absorbed returns to the soil with the mineralization of crop residues, which makes sorghum interesting for recycling this nutrient.

The topdressing application of N and K should be performed when the plants have seven fully expanded leaves, as long as until that stage, 40 kg ha^{-1} of these nutrients is available for plants.

The grain sorghum DKB 599 accumulates dry matter and macronutrients until the physiological maturity when it reaches the maximum accumulation.

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